679

VOLUME 81 SEPARATE No. 679

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

MAY, 1955

ANALYSIS OF CONTINUOUS STRUCTURES BY JOINT ROTATION

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STRUCTURAL DIVISION

{Discussion open until September 1, 1955}

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Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

THIS PAPER

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This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

ANALYSIS OF CONTINUOUS STRUCTURES BY JOINT ROTATION

Charles T. G. Looney,[1] A.M. ASCE

SYNOPSIS

A method of analysis is described for the determination of the moments in a continuous structure due to an unbalanced moment of unity at each joint. This method determines directly the relative stiffnesses of the members meeting at a joint restrained at the far ends by adjacent members, so that the unbalanced moment of unity can be proportioned directly between the members. Further, the carry-over moments to all the other members of the structure are determined directly.

In the process of designing a continuous structure several analyses must often be made. The determination of maximum stresses due to live load requires several analyses as do the computations for influence lines, the determination of the stresses due to temperature, shrinkage, settlement or sidesway. The method of analysis presented here offers a practical solution in the direction of simplification.

If repeated analyses are required, the labor can be reduced by the determination of the moments due to an unbalanced moment of unity at each joint. The analysis is then made by finding the fixed end moments due to any load or displacement and adding to these the product of the fixed end moment times the corresponding moments due to an unbalanced moment of unity. In this way the moments at the ends of all the members may be found. Given the moments at the ends, an analysis for shear, moment, or reaction may be separated into two parts; first, an analysis in which all members are considered simply supported, and second, an analysis considering only end moments. The total of the two parts gives the shear, moment or reaction.

The following method of analysis offers a new means of determining the moments in the structure due to an unbalanced moment of unity at each joint. This method determines directly the relative stiffness of the members meeting at a joint restrained at the far ends by adjacent members, so that the unbalanced moment of unity can be proportioned directly between the members. Further, the carry-over moments to all the other members of the structure are determined directly.

This method of analysis is illustrated by a three-span continuous beam with relative stiffnesses of 1:2:4, as shown on Figure 1, and a carry-over factor of -0.5 for all members. The moments at the ends of all the members are found, due to an external moment at the right end at D, and also due to a moment on the left end at A. These moments, due to a moment on the right end and on the left end, are proportional to the carry-over moments. The stiffnesses are obtained simultaneously from the same analysis.

The analysis for an external moment on the right end at D is shown in detail by a series of steps, and each step is illustrated by a deflected structure

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in order to emphasize the physical picture. The joints are rotated in order A, B, C and D from the left to right and the moments determined.

First, rotate joint A any amount, assuming the far end of the member to be fixed at B. An amount of +2 was assigned at A which determined the carry-over moment at B to be -1.

Second, rotate joint B to cancel the moment of +2 at A, assuming the far ends of the members to be fixed at A and C. Since A is hinged, the moment there should be zero. A carry-over moment of -2 from B will cancel the +2. The moment at B will therefore be +4 (-2 ÷ -0.5). The moment on the right of B, -8, is determined by the relative stiffness of the two member ($4 \times \frac{2}{1}$). The carry-over moment to C is +4.

Third, rotate joint C to balance the moment at B, assuming the far ends of the members to be fixed at B and D. The moment on the left of B is -1 + 4 = +3 and the moment on the right -8. These moments can be balanced by a carry-over moment of +11 from C. Thus, the moment on the right of B, -8 + 11 = +3 equals that on the left. Then the moment at C will be -22 (+11 ÷ -0.5). The moment on the right of C, +44, is determined by the relative stiffness of the two members ($22 \times \frac{4}{2}$). The carry-over moment to D is -22.

Fourth, rotate joint D to balance the moment at C, assuming the far end of the member to be fixed at C. A moment of -62 will balance the moment at C and the moment at D is therefore +124 (-62 ÷ -0.5). The last line of Fig. 1 shows the final moments due to an external moment on the right end at D.

This analysis, explained above in detail, is repeated in condensed form on Fig. 2, identified as "moments A to D". A similar analysis is carried out from right to left for a moment on the left end at A and is identified as "moments D to A".[2]

The analysis shown for the moments A to D and D to A is all that is required in order to obtain the moments due to an unbalanced moment of unity at each joint. The moments in the structure to the left of a moment of unity will be proportional to the moments A to D (0, +3, -18 and +102); and the moments in the structure to the right of a moment of unity will be proportional to the moments D to A (+51, -18, +6 and 0). These are therefore called carry-over factors to the left (moments A to D), and to the right (moments D to A). The moment of unity will be divided between the members at a joint in proportion to the relative stiffness when the far ends of the members are restrained by the adjacent members of the structure. The stiffness, when the far end is restrained by the adjacent members, will be called modified stiffness in order to distinguish it from stiffness as usually defined, with the far end fixed.

The modified stiffnesses of all members are shown on Fig. 2, and they are obtained directly from the moment analysis. The modified stiffness of BA is shown as $\frac{3}{4}$ of the stiffness of BA which is 1.[3] The final moment at B is +3, and the moment required to rotate B when the far end at A is fixed is +4. Therefore the modified stiffness of BA is $\frac{3}{4}$ of the stiffness of BA, which is

2. If the structure were symmetrical it would not be necessary to repeat this analysis.
3. These are actually relative modified stiffnesses since the, 1, is a relative stiffness.

1.[4] By this same reasoning, the modified stiffnesses of CB and DC are respectively $\frac{18}{22}$ x 2 and $\frac{102}{124}$ x 4. The modified stiffnesses at the left ends of the members are obtained from the analysis for the moments from D to A; by the same reasoning the modified stiffnesses of AB, BC and CD are $\frac{51}{56}$ x 1, $\frac{18}{20}$ x 2 and $\frac{6}{8}$ x 4.

The unbalanced moment of unity is divided between the members in proportion to the modified stiffnesses and the carry-over moments are proportional to the carry-over factors shown on Fig. 2. Figure 2 shows all the analysis necessary for the determination of the moments due to an unbalanced moment of unity at each joint A, B, C and D. If the structure were symmetrical, only half of these computations would be required.

For a clockwise moment of unity at A the moments will be proportional to the carry-over factors to the right (see Fig. 2). The moment at A will be +1.000 and the moments to the right proportional to the carry-over factors +51, -18, +6 and 0 will be +1.000, -0.353, +0.118 and 0 (see Fig. 3).

A clockwise moment of unity at B will be divided between the members in proportion to the relative modified stiffness (RMS) of the members at B. The RMS of BA is $\frac{3}{4}$ x 1 and the RMS of BC is $\frac{18}{20}$ x 2. Therefore the moment of unity is divided in this proportion: -0.294 on the left and +0.706 on the right. The moments to the right will be proportional to the carry-over factors to the right. The moments to the right proportional to the carry-over factors -18, +6 and 0 will be +0.706, -0.235 and 0. The carry-over factors to the left determine the moments to the left. The moments to the left proportional to the carry-over factors 0 and +3 will be 0 and -0.294.

A clockwise moment of unity at C will be divided between the members in proportion to the RMS of the members at C. The RMS of CB is $\frac{18}{22}$ x 2 and the RMS of CD is $\frac{6}{8}$ x 4. Therefore the moment of unity is divided in this proportion: -0.353 on the left and +0.647 on the right. The moments on the right proportional to the carry-over factors on the right, +6 and 0, will be +0.647 and 0. The moments on the left proportional to the carry-over factors on the left, 0, +3 and -18, will be 0, +0.059 and -0.353.

For a clockwise moment of unity at D the moments will be proportional to carry-over factors to the left. The moment at D will be -1.000 and the moments to the left proportional to the carry-over factors 0, +3, -18 and +102 will be 0, -0.029, +0.177 and -1.000.

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4. Another proof may be used

$$\text{Rotation of B, } \theta_{BA} = \frac{\text{Moment}}{\text{Stiffness}} = \frac{4}{S_{BA}}$$

$$\text{Modified Stiffness BA, } MS_{BA} = \frac{\text{Moment}}{\text{Unit Rotation}} = \frac{3}{\theta_{BA}} = \frac{3}{4} S_{BA}$$

Figure 4 gives an example of the use of these coefficients for an unbalanced moment of unity and shows how a repeated analysis may be simplified. In this example the load in span AB results in fixed end moments of -100. The FEM of -100 at A is a clockwise moment on the joint, so multiply the coefficients for an unbalanced moment of unity at A by 100. The FEM of -100 at B is a counter-clockwise moment on the joint so multiply the coefficients for an unbalanced moment of unity at B by -100. The final moments are obtained by adding the original FEM and the product of the FEM and the corresponding moment coefficients.

These moment coefficients are useful in the analysis for maximum moments, shears or reactions due to live load. The position of the live load can be determined approximately by means of a sketch of the influence line using Muller-Breslau's principle. With the approximate position known, a few computations, shifting the live load in this vicinity, will determine accurate maximum values. Moment coefficients can be used to determine maximum moment and shear diagrams simply by moving the live loads across the structure and making repeated analyses for the moment and shear diagrams for successive positions of the live load. The envelop of these moment and shear diagrams is the maximum diagram. The principle involved is very simple and the moment coefficients reduce the analysis to reasonable proportions.

Influence lines can be obtained by computing the quantity desired due to a load of unity for several positions on the structure. The moment coefficients are useful for this repeated analysis. A sketch of the influence line is valuable for placing the load of unity for a minimum number of controlling ordinates.

Where exact influence lines are required, the following systematic procedure using moment coefficients is particularly useful. This procedure is based on the fact that a continuous structure can be treated as a number of simply supported members with end moments. The moment, shear or reaction, due to any cause, can be computed as the sum of the moment, shear or reaction for a simply supported member and the moment, shear or reaction due to the end moments.

The influence line ordinates can therefore be obtained by combining the influence lines for simply supported members with influence lines for end moments. A systematic procedure would therefore consist of the following steps.

1. Compute the influence line ordinates with all members simply supported.
2. Find the moment coefficients for an unbalanced moment of unity at each joint.
3. Find the moment, shear, or reaction desired due to a fixed end moment of -1 at the ends of each member.
4. Multiply the results of 3 by the corresponding influence line ordinates for fixed end moment.

Add together the influence line ordinates from 1, for the simply supported beam, with the influence line ordinates from 2, 3 and 4 for the end moments. The use of influence line ordinates for fixed end moments is convenient since accurate tables of influence line ordinates for fixed end moments have been published.[5]

This method of analysis is applicable to continuous beams and viaducts. The analysis can be applied to building frames under conditions where "the

5. Handbook of Frame Constants. Portland Cement Association.

live load may be considered to be applied only to the floor under consideration, and the far ends of the columns may be assumed as fixed".[6] It provides for a systematic computation of the maximum moments and shear for building frames with full span loading. The reduction of labor and the systematizing of computations made possible by this method of analysis makes the computation of maximum stresses and the study of variables a practical design office procedure.

Figure 5 illustrates the use of this method of analysis for a part of a building frame with the columns fixed top and bottom. The relative stiffnesses are 4 for the beams, 1 for the exterior and 2 for the interior columns. The carry-over is assumed to be -0.5 for all members.

The dead load moment and the maximum live load moment will be computed at the ends and center of each span. The steps in this analysis are as follows.

1. Compute the moment coefficients for the ends of the beams for an unbalanced moment of unity at each joint.
2. Compute the moments at the ends and centers with each span loaded separately. Assume fixed end moments of -1 and a total moment of +1.5 (this is proportional to fixed end moment of $-\frac{1}{12} w L^2$ and total moment of $+\frac{1}{8} w L^2$).
3. Add all moments (2) to obtain dead load moment coefficients.
4. Add all positive moments (2) to obtain maximum positive live load moment coefficients and add all negative moments (2) to obtain maximum negative live load moment coefficient.

Figure 5 shows the moments, determined as before, as the joints are successively rotated from left to right. Starting at the left, A is rotated and the moments +8, -2 and +2 are selected in proportion to the relative stiffnesses of the members. Then B is rotated to balance A and -12, the carry-over moment from +24 at B, is required at A to bring about this balance. The other moments at B, -12, -24 and +12, are proportional to the relative stiffnesses of the members. This procedure, illustrated in detail on Fig. 1, is followed to the right end E. The relative modified stiffnesses of BA, CB, DC and ED can be determined as shown on the figure. The carry-over factors are obtained from the beam moments and are for moments to the left of the unbalanced moment of unity.

The relative modified stiffnesses for AB, BC, CD and DE are the reverse of the computed ones because of symmetry. The carry-over factors for moments to the right of the unbalanced moment of unity are the reverse of the computed ones. This analysis is all that is required for the computation of the moment coefficients for the frame.

For a clockwise moment of unity at E the moments will be proportional to the relative modified stiffnesses of the members at E, so the beam moment at E will be 3.66 (3.66 + 1 + 1) = 0.647. The moments to the left are proportional to carry-over factors to the left -4, +20, +44, -124, -260, +724, +1516 and -4220. For a clockwise moment at D the beam moment on the left is 3.66 (3.66 + 2 + 3.33 + 2) = 0.333 and on the right 3.33 (3.66 + 2 + 3.33 + 2) = 0.303. The moments on the left are proportional to the carry-over factors on the left -4, +20, +44, -124, -260 and +724; and the moments on the right are proportional to the carry-over factors on the right +20 and -4.

6. A C I Building Code (318-51) p. 610, 702 (a).

The moments due to a clockwise unbalanced moment of unity at C, B and A are found in the same manner. The moments due to a load in each span can now be computed easily. Fixed end moment of -1 and a total moment of +1.5 will be assumed. With span AB loaded, there will be fixed end moments at A and at B of -1. To these moments add the moment coefficient for unity at A and subtract the coefficient for unity at B. For example, the moment at A is -1.000 + 0.647 -0.061 = -0.414, and at B, -1.000 - 0.232 + 0.303 = -0.929 (left) and -0.111 - 0.333 = -0.444 (right). If the moment at the center is required, it can be obtained from these end moments since the moment at the center is equal to the average of the end moments. In the loaded span the positive +1.5 must be added to the average end moments. For example, in span AB the average end moment is $\frac{1}{2}$ (-0.414 - 0.929) = -0.672 which, when added to the total positive of +1.5, gives +0.828 for the moment at the center of AB. At the center of BC the moment is $\frac{1}{2}$ (-0.444 + 0.160) = -0.142, the average of the end moments.

For a load in span BC there will be fixed end moments of -1 at B and C to which the moment coefficients for unity at B are added and from which those for unity at C are subtracted. This is a repetition of the procedure for AB. Given the moments due to loading each span separately, the dead load moments and the maximum live load moments are obtained by simple addition. For dead load all moments are totaled since all spans are loaded. For maximum positive live load moments all positive moments are totaled and for maximum negative live load moments all negative moments are totaled.

Since these moments are for a fixed end moment of -1, the maximum dead plus live load moments are obtained by multiplying by the actual fixed end moments and adding.

The analysis as described is limited to continuous beams, viaducts, and building frames fixed at the top and bottom of columns as in the example. The effect of sidesway of viaducts can be introduced so that the moment coefficients include this factor. This analysis can be used on building frames. When turning the successive joints in a building frame a closed path is possible. This complicates the analysis and the marked simplicity shown by the examples given is lost.

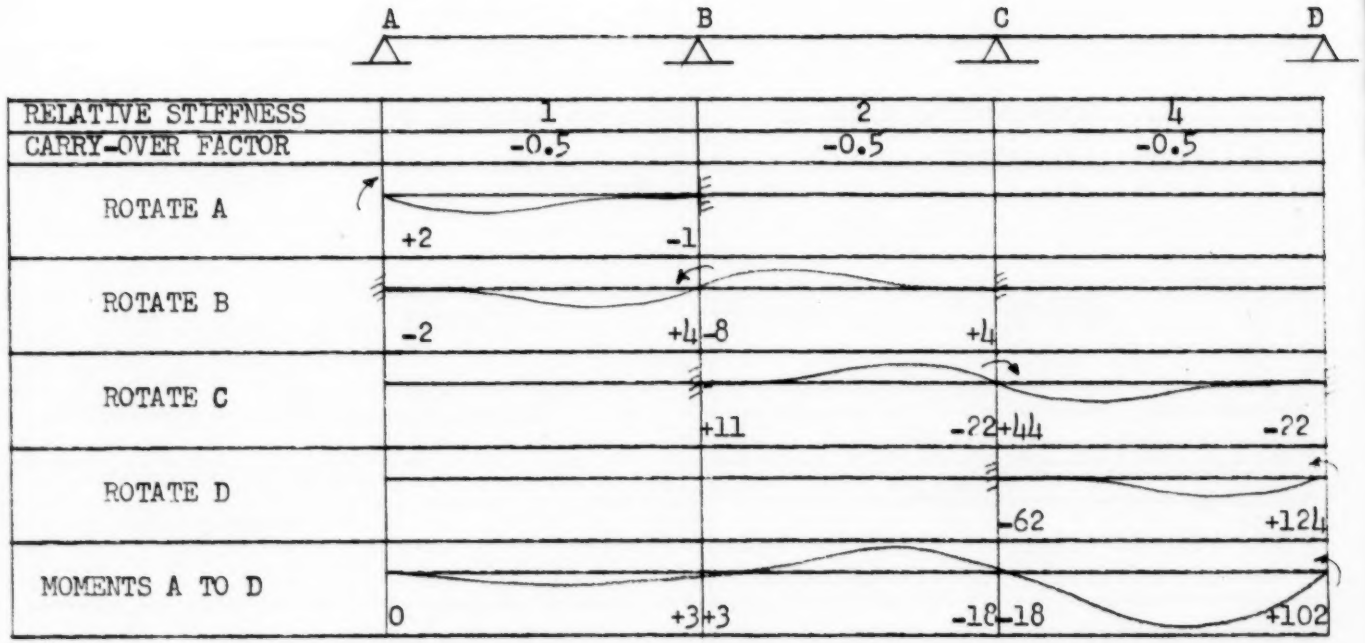


Figure 1

Analysis of Three-Span Continuous Beams

	A		B		C		D
RELATIVE STIFFNESS		1		2		4	
CARRY-OVER FACTOR		-0.5		-0.5		-0.5	
MOMENTS A TO D	+2	-1	-8	+4	+44	-22	
	-2	+4	+11	-22	-62	+124	
CARRY-OVER FACTORS TO THE LEFT	0	+3	+3	-18	-18	+102	
MODIFIED STIFFNESS RIGHT END		$BA=\frac{3}{4}X1$		$CB=\frac{18}{22}X2$		$DC=\frac{102}{124}X4$	
MOMENTS D TO A	-5	+10	+2	-4	-2	+4	
	+56	-28	-20	+10	+8	-4	
CARRY-OVER FACTORS TO THE RIGHT	+51	-18	-18	+6	+6	0	
MODIFIED STIFFNESS LEFT END	$\frac{51}{56}X1=AB$		$\frac{18}{20}X2=BC$		$\frac{6}{8}X4=CD$		

Figure 2

Analysis of Three-Span Continuous Beams (Condensed)

	A		B		C		D
R M S	$\frac{51}{56}$ X1						
C O F	+51	-18	-18	+6	+6		0
UNBALANCED MOMENT OF UNITY AT A	+1.000	-0.353	-0.353	+0.118	+0.118		0
R M S		$\frac{3}{4}$X1	$\frac{18}{20}$X2				
C O F	0	+3	-18	+6	+6		0
UNBALANCED MOMENT OF UNITY AT B	0	-0.294	+0.706	-0.235	-0.235		0
R M S				$\frac{18}{22}$X2	$\frac{6}{8}$X4		
C O F	0	+3	+3	-18	+6		0
UNBALANCED MOMENT OF UNITY AT C	0	+0.059	+0.059	-0.353	+0.647		0
R M S						$\frac{102}{124}$X4	
C O F	0	+3	+3	-18	-18	+102	
UNBALANCED MOMENT OF UNITY AT D	0	-0.029	-0.029	+0.177	+0.177	-1.000	

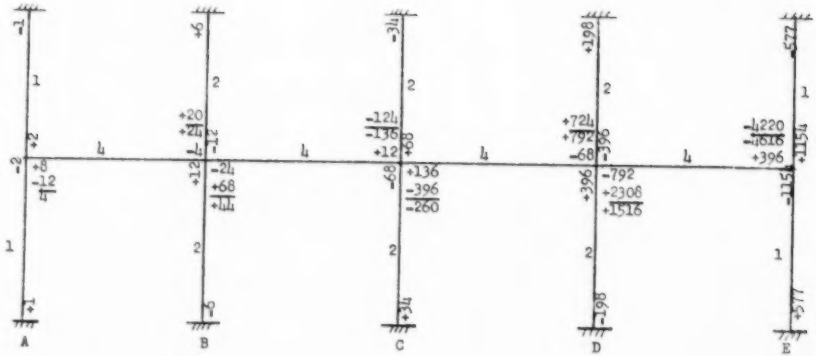
Figure 3.

Moments due to an Unbalanced Moment of Unity.

	A	B		C		D
F E M	-100	-100				
(A) TIMES 100	+100	-35	-35	+12	+12	0
(B) TIMES -100	0	+29	-71	+24	+24	0
FINAL MOMENTS	0	-106	-106	+36	+36	0

Figure 4.

Example of Use of Moment Coefficients



	A		B		C		D		E
R M S	3.66	$\frac{20}{24}X_1$=3.33	3.66	$\frac{124}{136}X_1$=3.65	3.65	$\frac{724}{792}X_1$=3.66	3.33	$\frac{1220}{4616}X_1$=3.66	
C O F TO THE LEFT	-4	+20	+44	-124	-260	+724	+1516	-1220	
C O F TO THE RIGHT	-1220	+1516	+724	-260	-124	+44	+20	-4	
UNITY AT E	-0.001	+0.009	+0.007	-0.019	-0.040	+0.111	+0.232	-0.187	
UNITY AT D	+0.002	-0.009	-0.026	+0.057	+0.120	-0.333	+0.303	-0.061	
UNITY AT C	-0.010	+0.052	+0.115	-0.323	+0.323	-0.115	-0.052	+0.010	
UNITY AT B	+0.061	-0.303	+0.333	-0.120	-0.057	+0.020	+0.009	-0.002	
UNITY AT A	+0.647	-0.232	-0.111	+0.040	+0.019	-0.007	-0.003	+0.001	
SPAN AB LOADED	-0.414 +0.628	-0.929	-0.444 -0.142	+0.150	+0.076 +0.024	-0.027	-0.012 -0.004	+0.003	
SPAN BC LOADED	+0.071 -0.112	-0.355	-0.782 +0.110	-0.797	-0.397 -0.122	+0.135	+0.061 +0.024	-0.012	
SPAN CD LOADED	-0.012 +0.024	+0.061	+0.135 -0.122	-0.380	-0.797 +0.110	-0.782	-0.355 -0.142	+0.071	
SPAN DE LOADED	+0.003 -0.004	-0.012	-0.027 +0.024	+0.076	+0.150 -0.142	-0.444	-0.929 +0.628	-0.414	
DEAD LOAD	-0.352 +0.706	-1.235	-1.118 +0.475	-0.941	-0.941 +0.475	-1.118	-1.235	+0.706	-0.352
LIVE LOAD POSITIVE	+0.074 +0.852	+0.061	+0.135 +0.734	+0.236	+0.236 +0.734	+0.135	+0.061	+0.852	+0.074
LIVE LOAD NEGATIVE	-0.126 -0.146	-1.296	-1.253 -0.864	-1.177	-1.177 -0.204	-1.253	-1.296	-0.146	-0.426

Figure 5

Analysis of a Building Frame.

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MARCH: 634(PO), 635(PO), 636(PO), 637(PO), 638(PO), 639(PO), 640(PO), 641(PO)[c], 642(SA), 643(SA), 644(SA), 645(SA), 646(SA), 647(SA)[c], 648(ST), 649(ST), 650(ST), 651(ST), 652(ST), 653(ST), 654(ST)[c], 655(SA), 656(SM)[c], 657(SM)[c], 658(SM)[c].

APRIL: 659(ST), 660(ST), 661(ST)[c], 662(ST), 663(ST), 664(ST)[c], 665(HY)[c], 666(HY), 667(HY), 668(HY), 669(HY), 670(EM), 671(EM), 672(EM), 673(EM), 674(EM), 675(EM), 676(EM), 677(EM), 678(HY).

MAY: 679(ST), 680(ST), 681(ST), 682(ST)[c], 683(ST), 684(ST), 685(SA), 686(SA), 687(SA), 688(SA), 689(SA)[c], 690(EM), 691(EM), 692(EM), 693(EM), 694(EM), 695(EM), 696(PO), 697(PO), 698(SA), 699(PO)[c], 700(PO), 701(ST)[c].

c. Discussion of several papers, grouped by Divisions.

e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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